Long-term Landscape and Fire History of Riparian Areas of New Mexico: the Geoarchaeological Survey of the Rio Puerco Basin and its Associated Tributaries around Guadalupe Pueblo

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Long-term landscape and fire history of riparian areas of New Mexico: the geoarchaeological survey of the Rio Puerco basin and its associated tributaries around Guadalupe

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The project

Fire and its relationship with humans and their use and abuse of the landscape have long been a strong interest to ecologists and archaeologists alike. The recognition of natural versus deliberately set fires by humans has involved many studies, ranging from those with a purely ecological focus on the past (Law 1998) or present (Perkins 1972; Mitchell 1992), to archaeologists and palaeoenvironmentalists investigating the signatures of fire on archaeological sites and in adjacent lakes and peat bogs from the Upper Palaeolithic onwards (Mellars 1976; McKinley 1997; Mellars and Dark 1998) to others looking at the indications of burning in soils and sediments (Bellomo 1993; Mckinley 1997; Marshall 1998; Canti and Linford 2000).

Much more work has been done by researchers working for various forestry services on the imprint of fire in ecological systems. This line of research is particularly well developed in the United States (eg. Wright and Bailey 1982; Wells *et al.* 1979; DeBano 1991). For example, at a symposium session on "how fire affects archaeological site interpretation and management" at the Society of American Archaeologists in Denver (April, 2002), every speaker documented recent experimental work on the spread, timing and temperature gradients of deliberately set and natural lightning strike fires in national/archaeological parks in the southwestern United States. It was generally observed that the largest fires were a result of lightning strikes, with fires caused by people being much smaller in size and extent of influence. The heating effects of fire below ground were also found to be negligible (*cf.* Canti and Linford 2000). The fire front passes quickly by, often in a few minutes, with flames remaining for a few hours at most, with heat retention only coincident for those same few hours. It is only next to fallen tree trunks/logs that there was significant heating and/or effects on archaeological artefacts. In conclusion, it would seem that there has to be special conditions for a surface fire to have any dramatic and long-lasting effect on the soil beneath, such as the presence of burnt tree stumps or fallen trunks, hearths or industrial processes.

Fire history has traditionally been investigated by two main methods. First is the study of fire-scared growth rings on trees with the associated analysis of the stand ages of trees which depend on fire to aid regeneration (Baillie 1995, 137; Swetman 1993). The second method has been

through the observation and analysis of the changes in types and abundance of micro-charcoal in lake sediment cores (Dark 1998; Hather 1998; Mellars and Dark 1998), although this method is often frought with interpretative problems caused by taphonomic processes of charcoal inclusion and preservation. More recently, these two methods have been augmented by the experimental approach (eg. Canti and Linford 2000), which may have either an ecological and/or archaeological focus and questions to address.

This project aims to investigate the palaeo-environmental circumstances of the effects of fire on Paleo-Indian, Archaic, Anasazi and modern landscapes in New Mexico. It will attempt to locate, contextualise and analyse past sequences of fire signals contained in the associated river valley sediment histories to generate models of the coincident criteria responsible for landscape degradation in this part of the southwestern United States.

Specifically, the project set out to investigate the late Pleistocene and early Holocene history of a part of the Rio Puerco river valley and its associated tributaries in northern New Mexico (Fig. 1) using geoarchaeological techniques applied in combination with palynological and micro-charcoal methodologies, supported by extensive radiometric dating. The geoarchaeological survey involved the sedimentary description of continuous exposed sections of the Rio Puerco near Guadalupe ruin, an Anasazi era pueblo associated with Chaco Canyon, as has been done in the lower Puerco basin by Love *et al.* (1982). But this study specifically focuses on buried soil/alluvial contacts and fire reddened lenses in different parts of the alluvial sequence. We conducted descriptive studies of the stratigraphy of the floodplain and valley deposits combined with targeted sampling for micromorphological, palynological analyses and radiocarbon assay, and prospection for buried archaeological features in the alluvial floodplain. Although this type of geoarchaeological survey is not new (*cf.* Waters 1992; Rapp and Hill 1998; French 2003a), it has rarely been used to reconstruct the history of forest fires from alluvial sediments and their signatures as a component of a changing landscape system over the long-term is a new approach. Using these combined data within a series of GIS models should enhance our understanding of the factors which may have lead to increased fire incidence and greater fire risk periods. It may even be possible to suggest ways of sustaining these landscapes in the face of the continuing threat of destruction by fire (after Chambers and Miller 2004), and in particular, contribute to decision-making about future fire management and riparian restoration efforts in the southwestern United States.

The geoarchaeological survey

Three field seasons of geoarchaeological survey have now been completed in the Rio Puerco basin just southwest of Cuba, New Mexico, focused on a 5km stretch of the Rio Puerco channel centred on the Guadalupe ruin and the lower reaches of four associated tributaries, Canons Tapia, Salada, Guadalupe and 'No Name' (Figs. 1-4). Analyses to date have addressed the sedimentary/soil sequences through palynological, micromorphological and dating analyses.

Rio Puerco

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centred on the Guadalupe ruin and the lower reaches of the associated tributaries, Canons Tapia, Salado, Guadalupe and an unnamed canon between the latter two canons. Analyses to date have addressed the sedimentary/soil sequences through palynological, micromorphological and dating analyses. The sequences observed are now beginning to exhibit similar and recurring features as set out below (Figs. 4-6; Tables 1-3).

The present day courses of the Rio Puerco and the four canons are a result of incision and down-cutting caused by thunderstorm events and associated sediment run-off from the immediate valley catchment. This combination of events was probably caused by the combination of sparse vegetation cover and the semi-arid climatic conditions, aggravated by intensive livestock grazing during the 19th and early 20th centuries (Scholl and Aldon 1988; Phippen and Wohl 2003). In places it has resulted in some infilling and the creation of terrace benches within the valley floor that define about 4 metres above the river's base. The most extreme period of incision and terrace formation are believed to have occurred between 1885 and 1890, immediately after the area was stocked with cattle (Bryon 1925 & 1928; Hall 2004).

The present day incised channels of the Rio Puerco and associated canons/arroyos have created *c.* 11-12 metre high sections through the middle Holocene sediment record of this landscape (Fig. 4). The meandering Puerco river course and the lower reaches of the tributary canon courses occupied an active alluvial floodplain in the middle Holocene from about 6000-2500 BC, or the earlier to middle Archaic period. The sediments infilling this alluvial floodplain are ostensibly very fine to fine sand and silt deposited by run-off and sheet erosion processes, possibly on a seasonal basis, and are suggestive of and similar to the present landscape of open to scrubby, poor grassland and semi-arid conditions. Within this aggrading drainage system, there appear to be at least three major episodes of stabilisation that are consistently evident that are associated with distinct evidence of incipient soil formation (Tables 1 & 2).

The aggrading sequence begins with laminated silty clays indicative of shallow and still water overbank flooding conditions. This is soon followed by increased erosion and run-off, greater water velocities and the repeated deposition deposition of fine sands and silts over a depth of greater than 4m in an aggrading floodplain situation. Although much of these deposits were obscured by recent face-fall deposits, the conjoining sequences in the Canons Tapia and Guadalupe exhibited the same sequence and signatures of repeated *in situ* fires and inwashings of fire-derived charcoal (see below). By implication, the dating from the Canon Tapia sequence suggests that this material accumulated from at least *c.* 6000 to 2570 Cal BC.

At about 2570-2330 Cal BC, the aggradational dynamic had slowed remarkably to a more seasonal, gentle and intermittent deposition of finer silt and clay, or overbank flood sediments. This represents a slowing in the aggradation of fine alluvial sediments in the valley system with vegetational development sufficient to add a significant organic component to the alluvial sediments, and finer silts and clays aggrading in shallow standing water conditions, probably on a seasonal basis. This has resulted in a series of at least three superimposed incipient soils being formed in a floodplain edge position that have developed over a depth of *c.* 1.3m and a relatively short time of 100-300 years, between about 2570 and 2280 Cal BC. At this stage, the river consisted of several, medium sized braided channels. The pollen data is suggestive of continuing but more variable, sparse pinyon-juniper woods, with willow and mesquite, sedges and saltbush

in the floodplain, as well as evidence for maize cultivation and charcoal associated with anthropogenic activities.

Cutting through this stabilisation zone and incipient palaeosols in at least three locations in the Rio Puerco and two instances in the Canon Tapia are open U-shaped cut features or ditches (Fig. 4). These ditches are *c.* 1.2m in width and up to 1m in depth and apparently aligned at a right-angle to the floodplain and current channel. These features are undoubtedly man-made as they are symmetrical and have distinct edge contacts with the alluvial subsoil deposits, and were sometimes re-cut on the same alignment. The ditches may have been dug to help drain a persistently slightly wetter zone in the seasonal floodplain of the day, or perhaps indeed to have been used to retain water and act as an irrigation ditch. In one case, the ditch is re-cut, and both deepened and widened on the same alignment (Fig. 4), and in another case, there is a second ditch defining another 2-3m above the main stabilisation zone and about 2m below the 1000-1400AD to modern valley base surface. The occurrence of these ditches at several locations in the study area suggests that they are indicative of a wider archaeological phenomenon and represent some degree of land management of from about 4,500 years ago, that is throughout the later Archaic period.

These ditches contained pollen data that indicated widespread moist grassland in this alluvial floodplain which would have encouraged game and a variety of exploitable floodplain edge plants. Whether the floodplain was deliberately managed and irrigated for maize agriculture is another question. Nonetheless, maize pollen has been extracted from the base of these ditch fills in the Rio Puerco, and is suggestive of some maize agriculture at about 2500 Cal BC. Certainly similarly positioned ditches in an alluvial infill sequence have been observed near the Zuni Pueblo on the Colorado Plateau some 100km to the west, where they are associated with maize agriculture that have been dated to about 3-4000 years ago (Damp *et al.* 2002).

There was then a return to a phase of an increased erosion and run-off marked by the deposition of fine sands and silt alluvial deposits. This phase is associated with a substantial meandering channel system and repeated signatures of past fire events. There was another stabilisation zone within incipient soil formation at about Cal AD 370-540, followed by renewed alluvial aggradation.

Just before AD 1000, there was a final return to a slower aggradational dynamic with the deposition of overbank flood, silty clay deposits, and the accumulation of some organic remains and incipient soil formation. This was associated with numerous small and shallow stream channels in a seasonally active braid plain. From about this time and the development of the Pueblo period settlements (to the 14th century AD) until the late 19th century, alluvial aggradation slowed dramatically and the drainage system appears to have reached a lengthy period of relative stability. There was a wide valley floor and a single large meandering river channel system. Certainly climatic modeling for this period suggests that this was a period of climatic variability and groundwater deficits making agriculture, and specifically maize cultivation, difficult, thus perhaps slowing the erosional dynamic of this landscape. Elsewhere in the region, there is evidence of a prehistoric arroyos such as the locally famous post-Bonito channel in Chaco Canyon, beginning to erode about AD 1000 (Bryan 1954; Hall 1977), but this has not been observed in the Puerco study area.

From the late $18^{th}/19^{th}$ centuries, there has been major incision (by up to *c*. 12-14 metres) through the pre-Pueblo (pre-14^{th} century AD) alluvial deposits and some infilling of the channel base creating a single inset terrace bench of historic age. The Rio Puerco arroyo fill incudes both point bar sands and oxbow low-water silty clays. The deposition of an inner fill terrace also occurred in all older tributary arroyos of the Rio Puerco.

The dating of this inset terrace bench has not yet been secured to better than the last 150 years. This has involved attempts to date the fill deposits using radiometric isotopes of cesium-137 and lead-210 (Pope *et al*. 1988; Hall 2004) and conventional radiocarbon dating in this project, with the suggestion that at least 30cm of oxbow sediment accumulation has occurred since 1950. Nonetheless, the formation of this bench may be ostensibly equated with greater run-off erosion associated with intensive grazing pressures associated with Navajo sheep rearing and Texan–style cattle ranching between the 1880s and the 1950s. Climatic factors such as greater dry conditions need not be the sole cause of this phenomenon, rather mis-management of this marginal landscape by extensive and over-intensive grazing is a more likely cause of the destabilisation. In the last few years, incision and the cutting of new gullies through the Puebloan period valley base is continuing, and this could be associated with the current ten-year drought period that this area is currently enjoying.

Depth (cm)	Sediment description	Pollen data	C-14 dating Cal AD/BC
surface	present day valley floor with Pueblo period (*c*. 1000-1400AD) remains; deep, sand infilled channels are incised from this level to the base of the present Rio Puerco (at *c*. 11m depth)		AD 1000 to present
6000-	stabilised fine sand and silty clay alluvium acting as modern soil profile since the Pueblo period		AD 1000 to present
1050-1100	fine sand/silt alluvium		
100-140	upper zone of slowly aggrading organic silty clay with columnar blocky ped structure; braided stream channels define at this level further downstream		AD 370-540
140-500	bedded fine sands and silts		
500-625	middle zone of three major horizons of slowly aggrading organic silty clay with columnar blocky ped structure; recut ditch defines at the base of this zone	localised pinyon-juniper woods with some oak, willow & mesquite; grasses & sedges common; moist areas	from 2570-2520, 2330 to 2480-2280 BC
c. 600	upper surface of inset terrace bench		AD1910-50 & AD 1650-1890

625-1050	bedded fine sands/silts/silty clay alluvial deposits; with large channels of braid plain defining at this level upstream and downstream	pinyon-juniper sparse woods with willow & diverse non-arboreal pollen; maize present; local fires	5750-5000 BC to *c.* 2500 BC
870-1000	recent section slumping		
1050-1100	lower stabilsation zone of slowly aggrading organic silty clays with columnar blocky ped structure developed on bedrock		
1100-1200	base of incised modern channel		AD1765 to present

Table 1: The typical valley infilling sequence in the Rio Puerco basin at Guadalupe, with the available pollen data summarised and radiocarbon dates

The tributaries

The Canons Tapia, Quadalupe and 'No Name' sequences were very similar, and a composite section is described below (Figs. 2 & 3; Table 2). Generally, the alluvial sequence and chronology of the tributary arroyos appears to match the major events observed in the same reach of the Rio Puerco. In contrast, Canon Salado was dominated by numerous inter-cutting channel deposits of all periods.

The section profile created by the 19/20th century AD incision of the current Canons Tapia, Quadalupe and 'No Name' provided a *c.* 10-11m deep section with the modern stream-bed defining at its base. Typically, the valley infilling sequence comprises a series of finely to coarsely bedded fine sands/coarse silts interrupted by occasional thin units of silty clay. At any of the unit contacts, and particularly above and below the middle zone of silty clay alluvial overbank aggradation, there frequently occur discontinuous 'fired horizons' comprised of wood charcoal and reddened zones of less than 1cm in thickness (Fig. 6). A typical section is described in Table 2 as follows:

Depth (cm)	Description	Dating (Cal BC/AD)
surface	present day valley floor with Pueblo period remains	
0-30	stabilised fine sand/silt alluvium	
625-1051	bedded fine quart sand, with some thin clay beds in the lower part of the unit with secondary carbonates throughout; basal contact is an erosional unconformity that may correspond to a channel with axial basalt gravels exposed downstream	
100-180	upper zone of slowly aggrading silty clays with columnar blocky structure; weak A horizon development at top of unit; split by two lenses of fine sand;	AD 370-540

	charcoal lens at *c.* 150cm; *in situ* burnt sediment lens at 165-170cm	
		-180-
215	bedded fine sand	
215-235	bedded fine sand and sandy silts	
235-245	finely bedded silty clay	
245-247	*in situ* burnt silt/very fine sand; with a hearth defining at this level	
247-310	bedded silty clays and fine sands	
310-425	bedded fine sand/silt with occasional silty clay lens	
425	discontinuous charcoal lens	
425-475	bedded fine sand/silt	
475-545	middle zone of slowly aggrading silty clays with columnar blocky structure; weak A horizon development at top of unit; burnt lens at 505-515cm	2480-2280BC to 2570-2520 & 2500-2330 BC
545-595	fine sand; base of this unit is erosional unconformity that corresponds to channel cut into lower unit just upstream which extends for c. 210cm below the base of this unit and is filled with gravels and cross-bedded sands	
595-630	bedded fine sand and silty clay with *in situ* burnt sand/silt zone at 610cm	date range of 3000 BC to 4000 BC
630-1000	alternating, bedded silty clay/fine sand with discontinuous charcoal at 655 and 760cm, and *in situ* sand/silt sediment zone at 760cm; ditches define at c. 700cm; also towards base small ditches at a right angle to the floodplain; the sharp basal contact is a minor erosional unconformity	
865-868	*in situ* burnt sand/silt	5750-5000 BC
870-1000	recent section slumping	
1000-1050	lower stabilsation zone of slowly aggrading silty clays with columnar blocky structure; weak A horizon development at top of unit (only evident in Canon Quadalupe)	
1000-1100	modern channel bed	AD1765 to present
1050-1100	*in situ* burnt lenses in alluvial silty clay lenses (only evident in Canon Quadalupe)	

Table 2: A composite profile description of the sequence in the Canons Tapia, Quadalupe and 'No Name', with typically the lower stabilisation zone only evident in the Canon Quadalupe (after French 2003b; Hall 2004, table 1 and fig. 4)

During the middle Holocene phase of erosion and alluvial deposition, there are numerous *in situ* signatures of small fires, which especially occur in the Canons Tapia and Quadalupe, and normally just after the deposition of thin lenses of alluvial silty clay. These are approximately dated to have occurred between *c.* 6000 and 2570 Cal BC. The question is - do these relate solely to periods of lower energy and relative stabilisation on the floodplain edge just after overbank flood events, and to lightning strike fires and/or to deliberately set fires to encourage grass and shrubby plant production as a food source for a variety of game animals, or burning of specific plant communities to increase the production of cultigens (such as maize) and other economic plants. It seems likely that the answer lies in a combination of those explanations. Certainly during this period there is evidence of a general increase in arboreal pollen, representing a sparse, surrounding pinyon-juniper woodland with small amounts of oak present, and willow, ash and birch suggesting extra moisture in the floodplain. A wide variety of non-arboreal pollen was also present which was indicative of grasses, sedges, saltbush, sagebrush, the occasional legume and also maize.

The alluvial sequence documented in these canons does not appear to correspond to the alluvial history of the Rio Puerco downstream as presented by Nials (2003, 32). The alluvial units are dissimilar, with the deposits in our study area dominated by clays, silts and fine sands whereas Nials' (2003) sequence was dominated by sand. In contrast to Nials' (2003) survey, we have recorded two periods of palaeo-channel incision in the Puerco in addition to the modern channel, rather than four. These are pre- and contemporary with the middle standstill horizon at *c.* 2500-2200 Cal BC, and near contemporary with the Puebloan valley floor.

The only other radiocarbon dated alluvial sequence from the region for comparison is from Chaco Canyon to the north and exhibits strong similarities to the Puerco observations. This exhibited two main periods of channel cutting in the past 7000 years, the first beginning at 2400 Cal BP and the last beginning at 1000 Cal BP (Hall 1977). The last one is the post-Bonito channel that formed while Puebloans were living at Chaco Canyon. Each episode of channel trenching was rapid and filling of the trenches probably occurred within 200 or 300 years of their initiation. The channel trenching documented by Nials (2003) between AD 1000 and 1200 is probably the same as that at Chaco. Indeed, sub-continent-wide channel trenching began throughout the plains and southwest about AD 1000 (Hall 1990).

Context	Radiocarbon years BP	Calibrated years BC/AD
present day valley floor	(Anasazi period pueblos on this surface)	AD 1000-1200
incision of current channels	(historical records)	begins in AD 1765 to present, mainly 1880-1950
inset terrace bench in present day bed of Rio Puerco	170 BP (& ring counts of cottonwood trees on this terrace bench suggest began to grow 70+ years ago)	AD 1650-1890 & AD 1910-1950 (Beta-186747)

upper standstill zone	1610 & 1620 BP	AD 370-540 (Beta-186730 & 186731)
fire lenses above middle standstill zone	3900 BP	2480-2280 BC (Beta-186733)
base of middle standstill zone	3950 BP	2330-2500 & 2520-2570 BC (Beta-186732 & 186734)
lower burnt zone	ranges from 4280 to to 6820 BP	ranges from c. 2870-5750 BC (Beta-186735, 186738-186740, 186743-186746)
with greater frequency of burning	from 4410 to 5310 BP and 6180 to 6820 BP	c. 3000-4000 BC & 5000-5750 BC

Table 3: Summary of radiocarbon dates of the major burnt and standstill zones

Fire

Evidence of fire has been found at all levels in the valley fill sequence in the study area, but primarily between the lower and middle stabilisation zone and just after the middle stabilisation zone over the period *c.* 6000-2200 Cal BC. In the Rio Puerco, this manifests itself as lenses of charcoal (as <3cm fragments) (Fig. 7), in places defining in 1-3cm thick lenses occurring for up to 20m in lateral extent. These charcoal lenses probably wash-out from either natural fires and/or human settlements in the valley system. In the Canons Tapia and Quadalupe, there are numerous 1-3cm thick lenses of *in situ* reddening of the fine alluvial sediments with included fine to coarse charcoal fragments (Figs. 6 & 8). These lenses often extend for up to 1.5m in lateral extent, and rarely up to 10m. These reddened lenses must represent *in situ* burning of organic material on the valley floor. It is suggested that this degree of reddening requires a fire of *c.* 500 degrees Centigrade for a period of at least 24 hours (after Canti and Linford 2000), and must therefore indicate the burning of fallen logs and tree trunks within the riparian areas which continue to burn after the fire-front has passed.

Micromorphology

A series of 25 intact soil/sediment block samples of major stratigraphic units and archaeological deposits were made into thin sections by Julie Miller of McBurney Geoarchaeology Laboratory, Department of Archaeology, University of Cambridge, following the methods of Murphy (1986). They were described using the international terminology of Bullock *et al.* (1985) and Stoops (2003).

Within the overall project aims, specific questions that the micromorphological analysis sought to address were as follows:
1) what comprised the laminated alluvial sediments in the Holocene infilling sequence of the Rio Puerco and Arroyo Tapia;

2) what characterised the stabilisation zones and/or incipient palaeosols in the alluvial infilling sequence of the valley system;
3) what form did the burning signatures take in thin section that may identify evidence of past *in situ* fires; and
4) was there any evidence of human land-use?

The salient results of this analysis are presented below.

The Rio Puerco

Samples taken from the basal fills of the double ditch feature associated with the major middle standstill horizon dated to about 2500-2200 Cal BC as exposed on the north side of the Rio Puerco near Guadalupe ruin (Fig. 4) exhibited a fining upwards sequence of fine sand to silt clay. These alternated in texture between finer and coarser facies indicative of greater and lesser water volume and velocity of overbank flooding. Throughout the profile there were intercalations of illuvial silty clay, organic and fine charcoal accumulation and secondary calcium carbonate formation indicative of alternating periods of shallow, standing water to dried out ditch base.

The transition zone between the tertiary fills of the ditches and the base of the subsequent palaeosol is composed of non-laminated silty clay with a minor very fine quartz sand component exhibiting a well developed sub-angular blocky ped structure. This fabric represents fines deposition in still water conditions that subsequently became stabilised and sufficiently well drained for long enough for soil mixing processes to occur and good structural organisation to develop, thus creating a soil. The upper part of the same palaeosol is a very fine to fine quartz sand with successive illuvial infillings of micro-laminated, dark brown or highly amorphous organic-rich, silty clay infillings of the void space. This suggests repeated depositions of fine colluvial (silty clay) and bioturbated amorphous organic matter, with much included fine charcoal resulting from fires also present. Then, this soil received successive within-soil intercalations of fine (silty clay) material which indicate that it is increasingly being affected by alternative wetting and drying episodes, and fines deposition in still water conditions, reflecting the seasonally active floodplain of the day. To conclude, this palaeosol is essentially associated with a very slowly aggrading, seasonal, flood meadow type of environment, but with sufficient organic accumulation, soil mixing processes and structural formation to develop into a soil.

This stratigraphic relationship of the palaeosol and the ditches could represent some early form of floodplain management of the terrace/floodplain in pre-Pueblo times at about 2300-2200 Cal BC. It is therefore of some importance in terms of past land management strategies in this landscape. Two other ditches were observed to define at this major standstill level elsewhere in the study area (ie. Just downstream in the Rio Puerco and in the Canon Tapia), and the one observed instance of ditch re-cutting suggests that there was a concerted attempt to maintain the system over time as it gradually became infilled with alluvially derived fine material.

The Canon Tapia

Several reddened or burnt units were sampled (Figs. 2, 3 & 6-8). In each case, alluvially derived fine sands to silty clay deposits similar to those in the Rio Puerco system are the norm. But, these units included greater or lesser amounts of fine charcoal (<2cm) (Fig. 7) and exhibited reddened

surfaces (of *c.* 1.5-3cm in thickness) (Figs. 6 & 8) as a result of associated burning and the oxidation of iron oxides. It is invariably the surface of the clay alluvial unit that is burnt. In order to get the burn to affect a 1-2cm depth of exposed sediment surface, there is an implied high temperature for a lengthy period, possibly approaching 500 degrees Centigrade over as long as 24 hours (after Canti and Linford 2000). This suggests that these fired zones typically represent the burning of a fallen log or *in situ* tree stump which continues to burn after the fire-front of a grass/scrub brush fire has passed. This in turn would seem to imply a much richer vegetation complex was present previously than exists today.

Discussion

It is apparent that there are a number of repeated but similar soil fabrics/sediment types occurring within the Rio Puerco drainage around Guadalupe ruin. These include very fine to fine quartz sand, inorganic and amorphous organic silty clay and very fine quartz sandy clay loam fabrics. The less common colluvial facies are represented by irregular aggregates of any or all of these fabrics occurring in any orientation, whereas the alluvial facies are finely bedded versions of the same three fabrics, with the thicknesses of the laminations varying from <0.5mm to about 5mm. Most fabrics contain a number of additions such as very fine to fine charcoal fragments which have invariably been degraded by later oxidation and insect/soil faunal digestion and bioturbation, as well as more minor quantities of animal bone and plant tissue fragments which have generally been replaced by amorphous iron.

There are a number of features that are indicative of the wetting and drying out of the fabrics, and which are either associated with or exacerbated by semi-arid to arid climatic conditions. These include the formation of lenticular gypsum in the pore space, amorphous and micro-sparitic calcium carbonate, and impregnation with amorphous iron oxides and hydroxides (or sesquioxides) and the presence of vughy or very porous fabrics which once contained a much greater organic component which has subsequently been oxidised.

Suggested interpretative middle-late Holocene valley sequence

The sequences observed in the Guadalupe study area exhibit similar features at certain levels that are repeated consistently and are revealing a consistent story.

The present day courses of the Rio Puerco and Canons Tapia, Salado, Guadalupe and 'No Name' are a result of incision and down-cutting caused by thunderstorm events and associated sediment run-off from the immediate valley catchment. These events were probably caused by the combination of sparse vegetation cover and the semi-arid climatic conditions, aggravated by intensive livestock grazing and lightning strike fires. In places it has resulted in some infilling and the creation of terrace benches within the valley floor that define about 4 metres above the river's base. The dramatic channel incision and subsequent terrace formation are believed to have occurred since about the 1880s (Bryon 1925 & 1928; Scholl and Aldon 1988; Phippen and Wohl 2003; Hall 2004).

The present day incised channels of the Rio Puerco and associated arroyos have created *c.* 11-12 metre high sections through the middle Holocene sediment record of this landscape. Substantial

meandering river (Rio Puerco) and tributary channel (Canons Tapia, and Quadalupe) courses occupied an actively aggrading alluvial floodplain in the middle Holocene from about 6000-2600 BC, or the earlier to middle Archaic period. The sediments infilling this alluvial floodplain are ostensibly very fine to fine sand and silt deposited by run-off and sheet erosion processes, possibly on a seasonal basis, and are suggestive of similar open to scrubby, poor grassland and semi-arid conditions as pertain at present. During this middle Holocene phase of erosion and alluvial deposition, there are numerous signatures of small fires, which especially occur in the Canons Tapia and Quadalupe, and especially occur just after the deposition of thin lenses of alluvial silty clay.

At about 2600-2300 Cal BC, the aggradational dynamic had slowed remarkably to a more seasonal, gentle and intermittent deposition of finer silt and clay, or overbank flood sediments. There were sufficient hiatuses in deposition to allow for organic accumulation and some soil structural development to begin, thus equating these horizons with incipient or raw organic soil formation. There appear to be at least four major episodes of stabilisation that are consistently evident in this drainage system. At this stage, the river consisted of several, medium sized braided channels. In addition, some ditches were deliberately cut at right angles to the contemporary river through these alluvial sediments/incipient soil horizons, possibly to aid drainage and/or to act as water storage ditches. It remains to be seen whether this alluvial floodplain was just supporting riparian vegetation and/or deliberately managed and irrigated for maize agriculture. Nonetheless, *Zea* or maize pollen has been extracted from the base of these ditch fills in the Rio Puerco, and is suggestive of some maize agriculture at about 2300 BC. Certainly similarly positioned ditches in an alluvial infill sequence have been observed near the Zuni Pueblo on the Colorado Plateau some 100km to the southwest, where they are associated with maize agriculture that have been dated to about 3-4000 years ago (Damp *et al.* 2002). This would be consistent with Matson's (1991, 252-8) model for early floodwater farming and the introduction of maize into the American southwest, as well as the management of grasses and shrubs for game animals.

There was then a return to a phase of an increased erosion and run-off marked by the deposition of fine sands and silt alluvial deposits. This phase is associated with a substantial meandering channel system and repeated signatures of past fire events. There was another stabilisation zone at about AD 370-540, followed by renewed alluvial aggradation.

Just before AD 1000, there was a final return to a slower aggradational dynamic with the deposition of overbank flood, silty clay deposits, and the accumulation of some organic remains and incipient soil formation. This was associated with numerous small and shallow stream channels in a seasonally active braid plain. This period of incision around AD 1000 was also observed to the north at Chaco Canyon (Bryan 1954; Hall 1977).

From the period of Pueblo settlements (11-14th centuries AD) until the late 19th century, alluvial aggradation slowed dramatically and the drainage system appears to have reached a lengthy period of relative stability. There was a wide valley floor and a single large meandering river channel system. This system became rapidly infilled by some major erosive events from time to time, probably quite late in this period, resulting in major channel avulsion across the floodplain. It may have also been responsible for the multitude of overlapping and inter-cutting channels observed in the Canon Salado.

From the late 18th/19th centuries, there has been major incision (by up to *c*. 12 metres) through the later and middle alluvial deposits and some infilling of the channel base creating inset terrace benches, probably in the last century. This may be equated with a return to greater run-off erosion associated with more intense grazing pressures associated with Navajo sheep rearing and Texan–style cattle ranching. Climatic factors such as greater dry conditions need not be the sole cause of this phenomenon, rather mis-management of this marginal landscape by over-intensive grazing is a more likely cause of the destabilisation. In the last few years, incision and the cutting of new gullies through the Pueblo period valley base is continuing, and this could be associated with the current ten-year drought period that this area is currently enjoying.

Climatic modeling

To develop the climatic aspects further, Linda Scott Cummings (2004) developed an archaeo-climatic model for the study area using data from Sante Fe, Utah, as the closest climatic station for which sufficient appropriate data exists. Graphs of monthly modeled mean temperature and precipitation were created using data averaged for every two centuries from 14,000 years BP to the present (Figs. 9-16; Table 4), and in combination with the examination of close interval pollen sampling were used to make inferences about past climate. In addition, these parameters may be used to generate a 'water budget', comparing precipitation and potential evapo-transpiration, wind speed and direction, storm intensity and frequency, snowfall, and other climatic factors (Bryson 1998; Bryson and Bryson 1997 & n.d.).

The archaeo-climatic model was constructed by incorporating the boundary conditions of reflected radiation from snow and ice, the July and January solar, global mean annual sea-surface temperatures also expressed as percent difference from present, and atmospheric carbon-dioxide concentration radiation for the northern hemisphere. This determined the insolation at the upper surface of the atmosphere for the past forty thousand years. Then, through a well-documented record of volcanic activity, an index of volcanic aerosols in the atmosphere (the primary agent preventing insolation) is calculated for the period from 14,000 BP to the present day. The information on insolation, energy budget and the position of restrictive elements in the atmosphere (ie. the jet stream, and permanently positioned high and low pressure zones) are compared statistically to 30-year average climatic data for a specific area. Small adjustments in the position of the previously mentioned restrictive elements in the atmosphere are made until the model explains over 98% (usually over 99.5%) of the observed climatic averages. Data points in the model reflect 200 year averages for climatic data and have been and are continuing to be ground-truthed through comparison with stratigraphic pollen and phytolith records, which indicate a high degree of reliability in the model.

Temperature

Beginning about 12,000 radiocarbon years ago at Santa Fe, temperatures began a steep, occasionally interrupted, rise until about 10,000 BP, when the increase halted and temperatures stabilized for about 2000 years (Fig. 9). Beginning about 8000 BP, temperatures resumed climbing into the middle Holocene and remained stable until 4000 BP (Fig. 9). Average annual temperatures varied around 1 to 2 degrees, between approximately 13 and 14.75 degrees C during this entire period. Temperatures decline sharply at 3900 BP, reflecting a period of intense,

prolonged volcanic activity that, through increasing the volcanic aerosols in the atmosphere, was responsible for lowering temperatures approximately 1.5 degrees C annually and a similar amount during the summer. Following this brief interval, annual temperatures returned to previous levels, fluctuating between 13 and approximately 14.2 degrees C until the intense Vandal Event, another volcanic event that lowered annual temperatures again. The last 2,000 years has been marked by fluctuations of approximately 2 degrees C, between lows of nearly 12.5 during the Vandal Event and 12.75 during the Little Ice Age to highs of approximately 14.5 degrees C at other times.

Precipitation and water supply

Modeled precipitation examines annual precipitation, as well as both July and August precipitation, as well as intensity history (Figs. 10 & 11). This model of precipitation for the Late Pleistocene/Holocene transitional period suggests conditions drier than today (Figs. 10 & 11). Modeled average annual precipitation between *c.* 14,000 and 11,400 BP wavered between about 165 and 200mm and from *c.* 11,400 to 7400 BP it increased slightly to 180 and 220mm. Between *c.* 7400 BP and 4200 BP annual precipitation is modeled to be relatively low and not variable, fluctuating between approximately 180 and 165mm. During these intervals the summer precipitation also has been relatively low, never exceeding *c.* 40mm in either July or August.

The Indus Event around 3900 BP marks the beginning of an increase in annual and summer precipitation from 185 to 240mm, while summer precipitation climbs from *c.* 25->50 mm in July and 35->60mm in August (Fig. 10). The Vandal Event at about 2000 BP is associated with a modeled sharp drop in both annual and summer precipitation (Fig. 10), indicating the probability that the storm track changed abruptly, resulting in a different water regime for several hundred years. From approximately 1600 BP conditions appear to have returned to those present prior to 2200 BP (Fig. 10), which is to say variable conditions marked by fluctuations in both annual and summer precipitation. This model of rainfall suggests that agriculture would have been very difficult in this area between approximately 2200 and 1800/1700 BP. This modeled drought should be examined in both the archaeological and archaeobotanical records for the region.

Rain intensity (Fig. 11) is modeled to have begun to decline just after it's peak at 11,800 BP, sliding from 11.5 to less than 9mm/day. Subsequently, intensity stabilized for about 2000 years until after 7800 BP, when it declined again to 8mm/day. The middle and late Holocene register relatively low but fluctuating annual precipitation intensities, between *c.* 8 and 9mm. In contrast, summer rainfall is modeled to increase in intensity after 5000 BP, peaking at over 10.5mm/day, then fluctuating between that level and 9.5mm/day until nearly the present. Summer rainfall intensity is modeled to drop to 9mm/day only during the period approximately 200 years ago and be relatively gentle but with occasional deluges.

The modeled water supply history (Fig. 12) combines precipitation history with potential evapo-transpiration. Annual precipitation has never equaled potential evapo-transpiration during the Late Pleistocene or entire Holocene, meaning that at no time during the modeled past has the area experienced a wet climate. The middle Holocene (*c.* 7500 and 4000 BP) is modeled to have been relatively drier than any other episode modeled, with the exception of the Vandal Event at *c.* 2000 BP. Annual precipitation has fluctuated between about 160 mm and 250mm annually, while potential evapo-transpiration has varied between slightly more than 400 and slightly less than 600mm annually. This leaves a water deficit of between approximately 250 and nearly 400mm

annually, and currently it is *c.* 300mm. It is interesting to note that both the Indus and Vandal Events correspond to modeled decreases in potential evapo-transpiration, and the Vandal Event is marked by a severe decrease in precipitation, meaning a change in storm track, and resulting in an even drier episode. In fact, even the Late Pleistocene and early Holocene, which were more mesic than any time more recently, were not significantly more mesic than at present.

About 11,000 years ago a sharp increase is modeled in the number of annual thunderstorms, which then holds relatively constant for the next 7000 years (Fig. 13). Indeed, the period between approximately 7500 and 5000 BP marks the lowest quantity of modeled annual and July/August thunderstorms of the Holocene. The period between 5000 and 4000 BP models variation and considerable increase in the July thunderstorms, and very little variability in the annual thunderstorms. Following 4000 BP and the Indus Event, the frequency of thunderstorms is modeled to increase dramatically, both in July/August and annually. This pattern holds true for most of the past 4000 years, with the exception of the interval known as the Vandal Event, around 2000 years ago. This interval is marked by a decline in modeled thunderstorm frequency. It is also modeled as a period of decreased precipitation.

Dewpoint is another factor important in understanding fire history (Fig. 14). The overall trend for dewpoint is increasing between approximately 8000 BP and the present. It is more pronounced for July than September, when the peak in dewpoint is noted before 2000 BP. Dewpoint is important in interpreting the potential fire threats because lightening associated with thunderstorms is more likely to start a fire at a low than a high dewpoint.

Dewpoint is the critical temperature at which condensation occurs, and thus, is a measure of how moist the air mass is. The lower the dewpoint, the lower the temperature must be to condense water vapor from the air. As the number of modeled thunderstorms is noted to rise, movement of the dewpoint is equally important in predicting fire hazard (Figs. 14 & 15). Therefore, relatively low modeled July dewpoints accompanied by large numbers of modeled thunderstorms suggests an increasing fire hazard. As the dewpoint rises, the fire hazard drops, even if the number of thunderstorms remains consistent. The period between approximately 7500 and 5000 BP is one of relatively few July thunderstorms and relatively high July dewpoint, suggesting low fire hazard. The July dewpoint continues to rise after 5000 BP when July thunderstorms are modeled to become highly variable. Portions of the last 4000 years appear to have had more fire hazard potential than others, as the thunderstorm frequency rose much faster than the dewpoint. The Vandal Event and the period approximately 200 years ago both appear to have been intervals of reduced fire hazard.

The annual snowfall also was modeled for Santa Fe (Fig. 16). It declined from more than 850mm/year between *c.* 14,000 and 6000 BP, when it averaged slightly more than 450mm/year. This is followed by approximately 2000 years of slightly fluctuating, but relatively minor snowfall where snowfall is modeled to have been between 450 and 500mm/year. The Indus Event appears to have sparked an increase in annual snowfall to more than 550mm/year around 3800 BP. After this, snowfall settled back down to previous levels, only to increase slightly during the Vandal Event to just over 500mm/year, approximately 2000 BP. Snowfall is modeled to have fluctuated slightly more during the past 2000 years, varying between *c.* 425 and 525mm/year.

The archaeo-climatic model provides information concerning potential temperature, precipitation, and fire hazard for the area. Comparison of the archaeo-climatic model with closely spaced and dated pollen samples from single, long stratigraphic columns has the potential to identify vegetative response to modeled changing climatic conditions, as well as record vegetation changes in response to local fires. Although these have yet to be sampled and analysed in sufficient detail for the Puerco study area, the Sante Fe climatic model suggests some trends which have undoubtedly played a role in the sedimentary and fire history of the study area.

Essentially there is a long-term trend to aridification associated with an increase in temperatures over the past 7000 years or so (Figs. 9-12; Table 4)). More importantly, over the last 5000 years, the July rainfall intensity has increased dramatically relative to the annual intensity (Fig. 11), and the frequency of July and August thunderstorms has increased dramatically over the last 4000 years (Fig. 13). As these occur when the land is driest and hottest, there is an increased risk of both fire hazard (Fig. 15) and erosion on increasingly devegetated surfaces over the last 5-4000 years. These modeled trends, if correct, when they are combined with the alluvial history, suggest the underlying reasons for the aggradation and incision geomorphic factors affecting this region. Here there is a landscape degradation trend associated with demonstrable climatic deterioration and human exploitation.

Radiocarbon years BP	Modeled climatic changes	Fire hazard	Puerco data
14000-6000	snowmelt decreasing		
6000-present	snowmelt fluctuating but increase at 3800 BP		
9000-present	rainfall intensity dropping long-term, but amplitude increasing; mean annual temperature increasing; decreasing snowfall	increasing long-term	
8000-present	dewpoint increasing, with peak just before 2000BP	decreasing lightning risk	
7500-5000	lowest quantity of annual and July-August thunderstorms		
7500-4000	low rainfall and low snowmelt lowest percentage of thunderstorms high dew point	lower fire hazard	frequent fires; erosion & alluviation; then stability
from 4000	frequency of thunderstorms increases dramatically, except around 2000BP		
from 3900	'Indus Event;' temperature declines sharply by 1.5C; thunderstorm frequency increases; increasing dew point	increased fire hazard	instability, erosion & alluviation
c. 3000-2000	period of increased snowmelt		instability; erosion & alluviation

from 2200	reduction in rainfall	drought; increased fire hazard	negative effect on agricultural crops
at 2000	"Vandal Event'; increased volcanic activity worldwide; decline in thunderstorm frequency; period of decreased rainfall; slight increase in snowmelt	reduced fire hazard	poor for maize crops
2200-1700	variable fluctuations in annual and summer rainfall		instability; erosion & alluviation
from 1600	climatic variability general water deficit	increased fire hazard	initial stability; then dramatic river incision
from 400	storm frequency has risen faster than the dewpoint	increased fire hazard	dramatic river incision; inset terrace formation

Table 4: The main trends in modeled climatic data abstracted from the Santa Fe derived climate model and an indication of the fire risk compared to with the soil/sedimentary data for the Rio Puerco study area

Conclusions

The riverine, incisional and depositional history of the Rio Puerrco basin study area around Quadalupe is exhibiting major and consistent trends. Two major sets of environmental parameters seem to pertain and alternate: phases of greater run-off, erosion, incision, deposition of fine sands/silts with large river meanders, all of which are associated with repeated fire signatures, alternating with periods of slower and finer run-off and overbank sedimentation and incipient soil formation, with smaller, braided stream channels in a wide and relatively stable floodplain, with occasional fire signatures. These erosion and fire events must be set against the modeled long-term aridification trend over the past 7000 years. Moreover, early on within this deteriorating system, there appear to be good archaeological indications of floodplain management in the Archaic period about 4500-4200 years ago.

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